Turbine Hot Section Material Development

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Turbine Hot Section Material Development

Blade team: Rebecca MacKay, Jim Nesbitt, Tim Gabb, Anita Garg, Rick Rogers, Jim Smialek, Mike Nathal

Disk Team: Tim Gabb, Jack Telesman, Chantal Sudbrack, Susan Draper, Anita Garg, Jim Nesbitt, Rick Rogers, Frank Ritzert
### NASA Subsonic Transport System Level Metrics

.... technology for dramatically improving noise, emissions, & performance

<table>
<thead>
<tr>
<th>TECHNOLOGY BENEFITS*</th>
<th>TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)</th>
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<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
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<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
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<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
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<tr>
<td>Aircraft Fuel/Energy Consumption† (rel. to 2005 best in class)</td>
<td>-33%</td>
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* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines.

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015.

† CO₂ emission benefits dependent on life-cycle CO₂e per MJ for fuel and/or energy source used.
Achieving N+2, N+3 Goals Requires Improved Materials Capability for Increased Turbine Temperatures

System Studies Results

Temperature, °F

Overall Pressure Ratio

GE-90 class
CFM-56 class

Tong et al, 2009
Guynn et al, 2009
Benzakein, 2008
Roadmap For Metallic Blade System

---|---|---|---|---|---|---|---|---|---
Low density single crystal alloy optimization | Alloy/Bond Coat/TBC/co-optimization | Adv Blade System | Component development – ERA follow-on
Creep/fatigue/environment failure mechanisms | Manufacturing demo | 
Space Act Honeywell | 
AFRL: Creep/TMF Life Prediction | AFRL: Future blade programs | 
Unfunded: New superalloys with alternate strengthening mechanisms for +200 F capability | 
Adv TBC development | 
Hybrid blades concept screening | Hybrid blades concept development | 
SRW | SFW | SUP | 

Fundamental Aeronautics Program
Subsonic Fixed Wing Project

ver. Oct 2010
Roadmap For Metallic Blade System

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<td>Goals</td>
<td>Low density single crystal alloy optimization</td>
<td>Alloy/Bond Coat/TBC/ co-optimization</td>
<td>Creep/fatigue/environment failure mechanisms</td>
<td>Space Act Honeywell</td>
<td>Manufacturing demo</td>
<td>AfRL: Creep/TMF Life Prediction</td>
<td>AfRL: Future blade programs</td>
<td>Unfunded: New superalloys with alternate strengthening mechanisms for +200 F capability</td>
<td>Low k TBC</td>
<td>Erosion resistant TBC</td>
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Development of High Temperature, Low Density Turbine Blade Alloys

• **Objective:**
  • Combine experiments and models to develop advanced turbine blade superalloys for a balance of all required mechanical and environmental properties
  • Optimize low density superalloy (LDS) single crystals for transitioning to industry

• **Approach:**
  • Design-of-Experiments approach for alloy development balancing creep strength, oxidation resistance, density, and microstructural stability.
  • Compare to predictions from commercially-available software tools based on multi-component thermodynamic modeling
  • Initial LDS alloys identified with +75°F capability; optimization round added +25°F
  • Alloy/Bond Coat/TBC co-optimization
    • Quantify the effect of substrate composition on TBC life with two different bond coats.
    • Quantify the effect of substrate composition and bondcoat on cyclic oxidation behavior without the TBC topcoat
Relative Performance of Low Density Superalloys (LDS) Against Baseline Rene N5

- Improvements in creep life of patented Round 1 alloy (LDS-1101) over commercial blade alloy (Rene N5) without reducing oxidation resistance
- Optimized alloy (LDS-4583) shows further increases in density-compensated creep capability over Round 1 alloy

Electron micrograph of alloy microstructure. Volume fraction of dark $\gamma'$ phase is crucial for alloy strength.

- New models closely predict microstructures from alloy compositions, whereas available, physics-based models grossly under-predicted amount of strengthening $\gamma'$ phase
- Fundamental studies on influence of microstructural parameters on creep life being finalized and journal article underway

*ICME: Integrated Computational Materials Engineering
Effect of substrate alloy composition on the thermal barrier coating (TBC) lifetime

Coatings:
- SOA commercial platinum aluminide bond coat
- SOA commercial ZrO$_2$-7wt.%Y$_2$O$_3$ top coat

TBC Lifetime (1-hr cycles at 1135°C)

- PtAl LDS 1101
- PtAl LDS 1101 + Hf

No Hf
105 1-hr Cycles

0.15 wt.% 265 1-hr Cycles

* Triplicate tests

Hf addition provides greater TBC lifetime
Similar TBC lifetimes observed on LDS alloy and commercial alloy

Coatings:
- SOA commercial platinum aluminide bond coat
- SOA commercial ZrO$_2$-7wt.%Y$_2$O$_3$ top coat

![Graph showing TBC Lifetime (1-hr cycles at 1135°C)](image)

<table>
<thead>
<tr>
<th>Coating</th>
<th>265 1-hr Cycles</th>
<th>305 1-hr Cycles</th>
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<tbody>
<tr>
<td>LDS 1101+Hf</td>
<td>272±12*</td>
<td>292±23*</td>
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<tr>
<td>CMSX-4</td>
<td></td>
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* Triplicate tests
Advanced bond coats show potential for increased TBC lifetime

Coatings: (1) SOA commercial platinum aluminide bond coat
(2) Advanced NiAl bond coat
SOA commercial ZrO$_2$-7wt.%Y$_2$O$_3$ top coat

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As-Coated

PtAl Bond Coat
265 1-hr Cycles

NiAl Bond Coat
386 1-hr Cycles
Cyclic oxidation behavior of coated LDS alloys

ΔW - Weight Change

No difference between LDS and CMSX-4 alloys with commercial platinum aluminide coating,
**Approach:**

- The most advanced turbine disks now in production operate at peak rim temperatures of ~1300°F (704°C) and are made from powder metallurgy (PM) alloys. Dual microstructure heat treatments are used to attain fine grain size in the bore for strength & fatigue resistance; and coarse grain size in the rim for creep & dwell fatigue resistance.

- The Air Force is pursuing an improved PM superalloy, to attain a peak rim temperature near 1400°F (760°C) using this approach.

- NASA SFW needs 1500°F (815°C) peak rim temperature to attain N+3 goals. This points to the need for more revolutionary concepts ⇒ **hybrid disk**

- First step: quantify maximum temperature capability of 3rd generation PM disk alloy and cast blade alloys, to select bore and rim materials.
Roadmap For Turbine/Compressor Disks

Understand life limiting failure mechanisms for current disk alloys and mitigation

1300F disk life system (alloy + coating); in collaboration with industry and AFRL

Understand chemistry-processing-microstructure-relationships (adv alloys) to identify development path to 1500F

1400F+ disk alloy system (alloy + coating) concept; collaboration with AFRL and industry.

AFRL 6.2: Hybrid Disk Program
Graded Prop Disk processing; Location specific lifing; Next Gen alloy dev.

Feasibility of 1400 F coating

1400 F disk component development – potential ERA follow-on

Hot spin test

TRL - 5

1500 F disk system concept screening (Hybrid disk)

TRL - 4

1500 F disk system development

Proposed NRA: Hybrid disk design trade studies

Proposed NRA: Hybrid disk joining dev

Aviation Safety  SFW
1500°F Hybrid Turbine Disk

Limited by time dependent properties: creep, creep-fatigue-environment interactions

Limited by fatigue and tensile (burst) strength
Varied Grain Size in PM Disk Superalloy LSHR and Cast Blade Superalloy Mar-M247LC, Added Single Crystal LDS

Coarse grain or single crystal

Fine grain
LSHR at 15 μm Grain Size Had Superior Strength and Ductility Near 1300°F (704°C), Needed for Hybrid Disk Bore and Web

But Single Crystal LDS Had Highest Strength and Ductility Near Hybrid Disk Rim Goal Temperature of 1500°F (815°C)
Single Crystal LDS Also Had Superior Creep Resistance at Hybrid Disk Rim Temperature of 1500°F (815°C)

All tested polycrystalline alloys

Single crystal cast superalloy (LDS 1101+Hf) showed 10X life improvement
Single Crystal LDS Had Superior Creep Over Hybrid Disk Rim Temperature Range

Creep benefit of LDS extends down to 1300°F (704°C)
Single Crystal LDS Showed Better Dwell Fatigue Resistance at Hybrid Disk Rim Temperature of 1500°F (815°C)

Tests at 1300°F (704°C) now getting underway
Influence of high temperature exposures on notched fatigue life of an advanced disk superalloy

Oxidation damage to ME3 disk surface

Exposure duration and temperature strongly impact low cycle fatigue response

Exposures in Air

- None
- 704 °C 100 h
- 704 °C 440 h
- 704 °C 2020 h
- 704 °C 100 h
- 815 °C 100 h
- 815 °C 440 h
- 815 °C 2020 h
- 815 °C 440 h

Vacuum

- 704 °C 124 ksi 20 cpm
- 815 °C 440 h
Hot Corrosion Trials on LSHR

- 32 h corrosion in air at 700°C using a salt paste of NaS\textsubscript{2}O\textsubscript{4} and MgSO\textsubscript{4}

Pit Depth Cumulative Distribution Plot

Pit depth where fatigue life is affected
Oxidation Resistance: LDS Showing Slower, More Stable Oxide Growth at Hybrid Disk Rim Temperature of 1500°F (815°C)

Disk alloys ME3, A10, LSHR form Cr₂O₃ external scale with Al₂O₃ subscale

LDS forms Al₂O₃ external scale

815°C (1500°F), 440 h
Roadmap For Turbine/Compressor Disks

**Understand chemistry-processing-microstructure-relationships (adv alloys)** to identify development path to 1500F

- **1500 F disk system concept screening (Hybrid disk)**
- **Aviation Safety**

**AFRL 6.2: Hybrid Disk Program**
- Graded Prop Disk processing; Location specific lifing; Next Gen alloy dev.
- **1500 F disk conceptual design**

**1300F disk life system (alloy + coating)**; in collaboration with industry and AFRL

- **1400F+ disk alloy system (alloy + coating)** concept; collaboration with AFRL and industry.
- **Feasibility of 1400 F coating**

**1400 F disk component development – potential ERA follow-on**

**1500 F disk system development**

- **Proposed NRA: Hybrid disk design trade studies**
- **Proposed NRA: Hybrid disk joining dev**

**TRL - 4**

**TRL - 5**

**TRL - 6**


**Understand life limiting failure mechanisms for current disk alloys and mitigation**

- Hot spin test

**1400 F disk life system (alloy + coating); in collaboration with industry and AFRL**

**2010**

**2011**

**2012**

**2013**

**2014**

**2015**

**2016**

**2017**

**2018**

**2019**

**14000 F disk alloy system (alloy + coating); in collaboration with industry and AFRL**

**2010**

**2011**

**2012**

**2013**

**2014**

**2015**

**2016**

**2017**

**2018**

**2019**

**1400 F disk component development – potential ERA follow-on**

**1400 F disk component development – potential ERA follow-on**

**1500 F disk system development**

**Proposed NRA: Hybrid disk joining dev**
Diffusion Brazing Used to Bond Single Crystal to PM Alloy

15 min vs 4 hr

CMSX-4
____
BRB
____
ME3

CMSX-4
____
BRB
____
ME3

CMSX-4
____
BRB
____
3D Strain Mapping During Tensile Testing of Hybrid Disk Coupon: ME3/BRB/CMSX-4: Room Temperature

Fracture location: in SX
3D Strain Mapping During Tensile Testing of Hybrid Disk Coupon: ME3/BRB/CMSX-4: 650°F(350°C)

Fracture location: at bond
3D Strain Mapping During Tensile Testing of Hybrid Disk Coupon: ME3/BRB/CMSX-4: 1300°F(700°C)

Fracture location: at bond
Conclusions

• Low density single crystals have very attractive balance of capabilities for turbine blades:
  – Improved temperature capability at lower weight (+100°F)
  – Thermal barrier /bond coat compatibility has been demonstrated
  – Looking to expand collaborative efforts with industry

• Compressor/turbine disk development being emphasized via coordinated efforts among NASA, DoD, and industry
  – N+2 requirements point to an extension of powder metallurgy-based approaches
  – Growing importance of environmental effects on mechanical properties
  – Projected N+3 requirements point to a hybrid architecture
  – Some building blocks to hybrid architecture concepts have been addressed
    • Relative performance of PM, SX, and cast alloys in critical mechanical properties
      – Tensile strength, creep life, dwell fatigue life, oxidation and corrosion resistance
    • Mechanical behavior of bonded specimens